Development of a Laser Micromachining Process for the Fabrication of SiC Mirrors

Technical Monitor: Dr. Lawrence Matson

MDA Phase II SBIR Contract # W9113M-06-C-0117

Mound Laser & Photonics Center, Inc.

Ron Jacobsen (P.I.)

Larry Dosser, Scott Cornell,

David Beeler, Chris Taylor

Contract Status

- Phase II concluded in December 2008.
- MDA Transition funding award for one full year additional effort announced August 2008. ETA = February 2009.
- Transition funding not yet awarded. ETA now June 2009.
- This presentation represents about 4 months worth of update relative to last year's presentation.

Program Goals

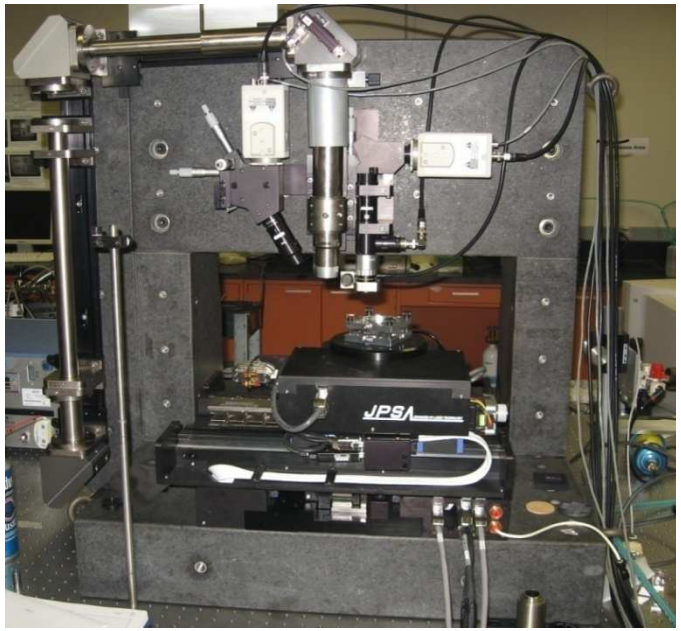
- Gain practical understanding of pulsed laser ablation of SiC materials being considered for mirrors.
  - Ablation rate
  - Machining quality
  - Roughness
  - Damage Mitigation
- Develop metrology guided laser micromachining algorithm for arbitrary shaping (e.g. aspheres) of SiC blanks
- Develop laser micromachining workstations for practical mirror shaping.

Laser and Materials

- Picosecond pulsed laser for direct ablation
  - Avoids thermal effects
  - Damage free
- SuperRAPID by Lumera
  - Pulse duration ~10-14 ps
  - Wavelength choices 1064, 532, 355 nm
  - Pulse frequency from 10 – 640 kHz
  - Nominal max power = 10W (a 50W version will be available soon.)
- Experimentation focuses on two SiC materials
  - Trex SiC: relatively smooth initially
  - Poco SuperSiC-2: very rough, but easy to make near net shape

Direct Focus Workstation

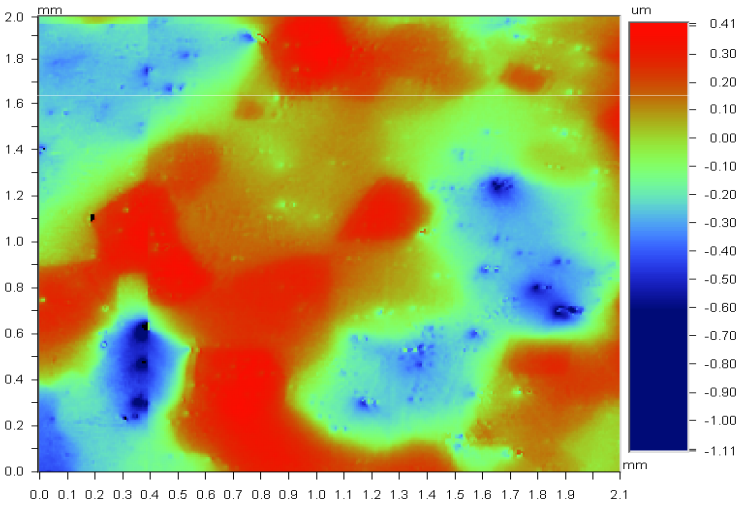
- Integrated by JPSA
  - Four axis (X,Y,Z,θ)
  - Direct focus, position synchronized laser firing
    - smaller laser spot, < 2 μm accuracy
  - Scan head
    - Faster operation, ~ 20 μm accuracy
  - Vision system
  - 6” turntable
- Enables
  - Greater positioning accuracy
  - Polar machining θ.
  - Room to add in situ metrology.



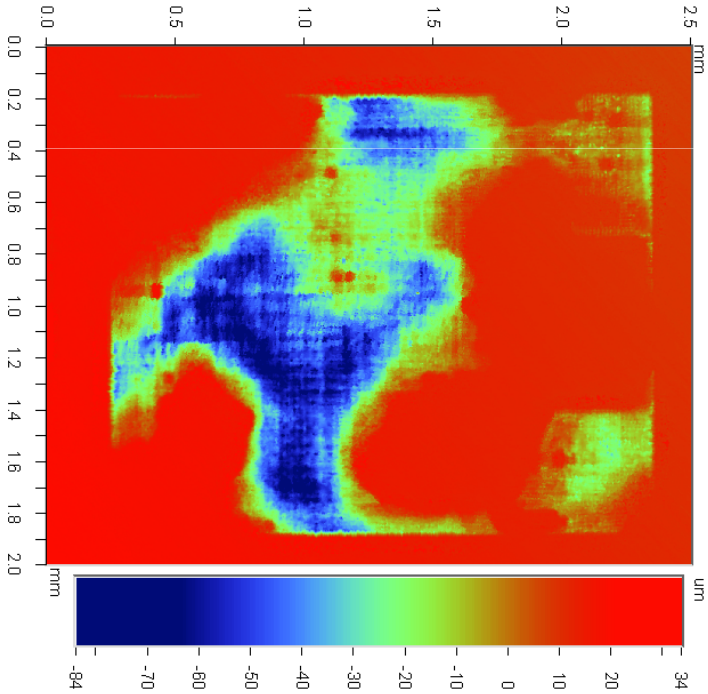
Metrology Guided Micromachining

MLPC and Wright State University, developed software to guide the laser workstation based on metrology of original surface.

- **Input:** Height map of surface from White light interferometry.



- **Output:** Laser path commands that machine the pattern below into a flat surface.

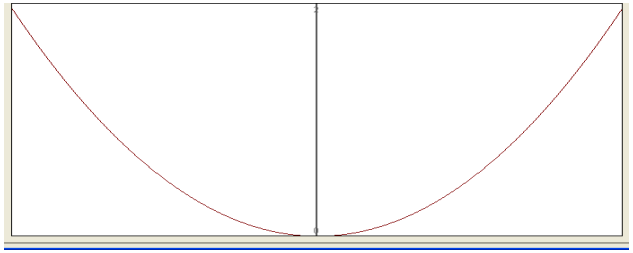


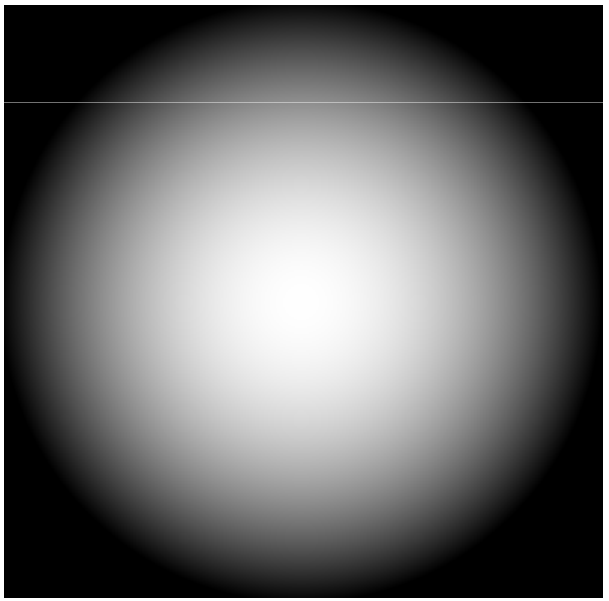
Metrology Guided Mirror Machining

- Inputs
  - Height map of original surface.
  - Mirror-shape equation.

$$Z = \frac{CS^2}{1+\left[1-(K+1)C^2S^2\right]^{1/2}}$$

- Output
  - Command file specifying laser paths and firing times needed to ablate from current shape toward final shape.





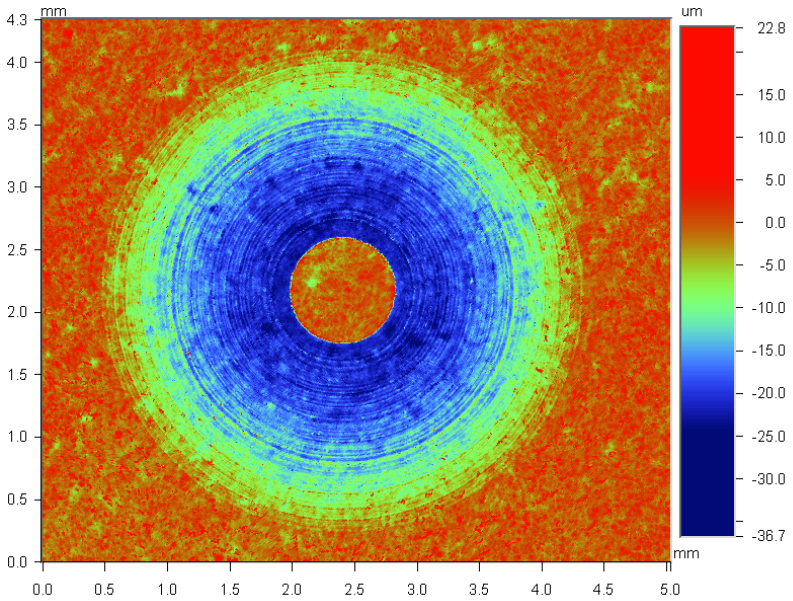
Machining on Direct Focus Workstation: Example 1.

When executing polar machining ON center …

- Machining is faster because the laser is always over the target.
- However, center is not accessible as there is a minimum radius at which appropriate laser pulse overlap can be maintained.

→ Appropriate for component that don't use center.

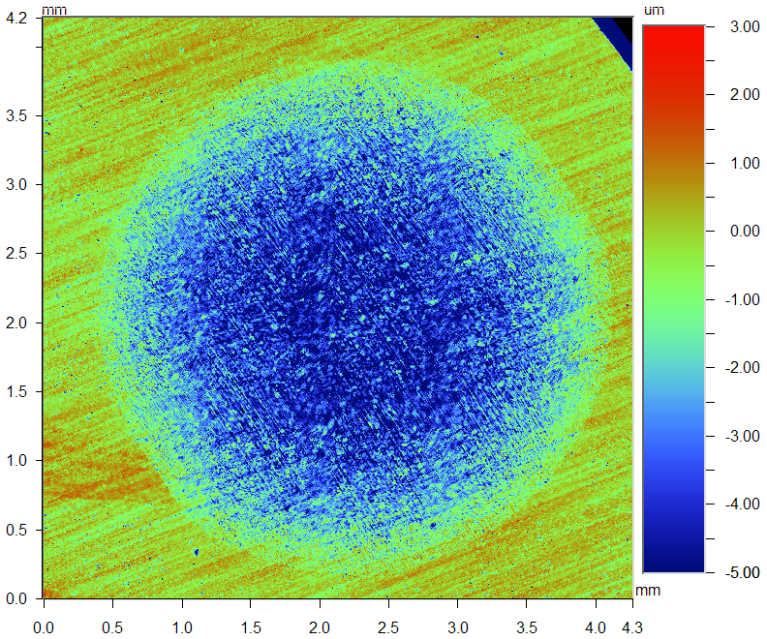
→ Or, a finishing step step can remove the central plateau.

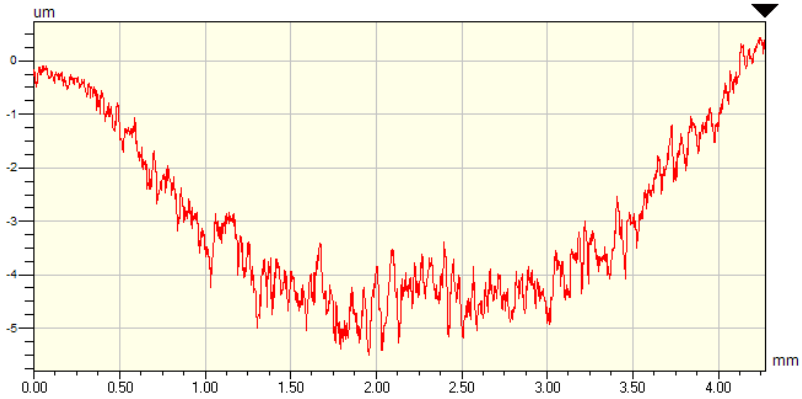


Machining on Direct Focus Workstation: Example 2.

When executing polar machining OFF center …

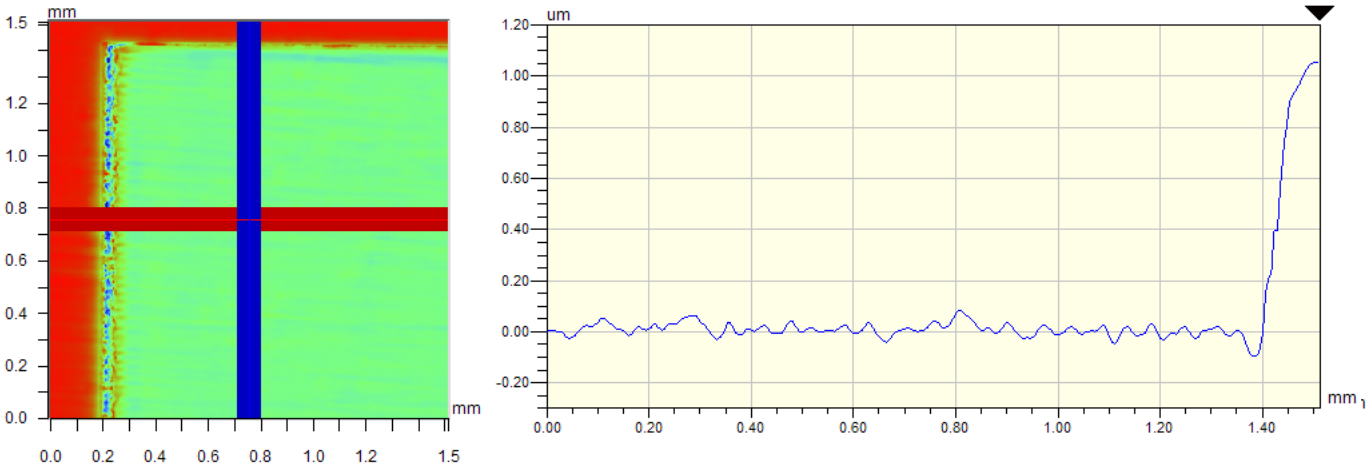
- Plateau in center is avoided.
- Machining is slower as laser is off target for most of each revolution.
  - → Efficiency could be increased by machining multiple parts per revolution.





Polishing Compatibility

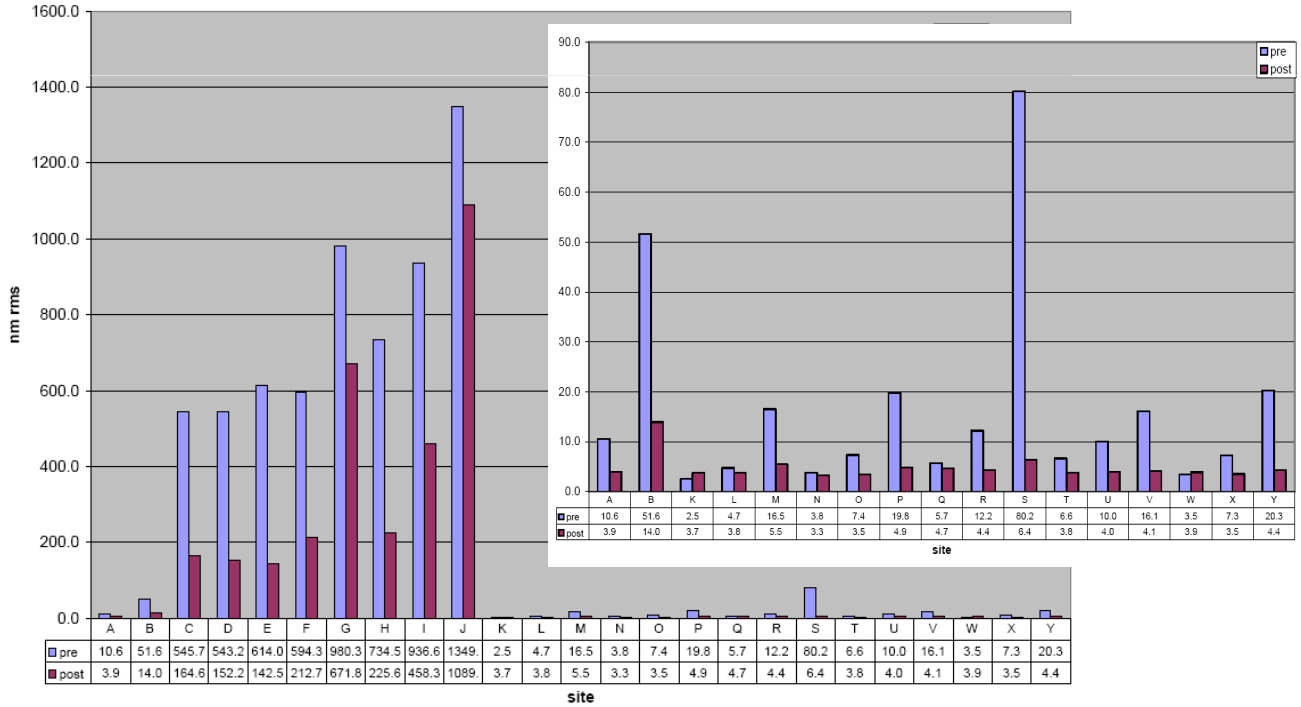
- An extensive study was undertaken in cooperation with QED to determine how much laser ablation induced roughness of SiC could be tolerated before polishing.
- Began with Trex SiC polished to ~ 4 nm Ra.
- Laser ablated regions of sample with varying pulse energy and raster pattern to create surfaces with roughness from 10 nm to > 10,000 nm.
- Sample was then given to QED for MRF polish.



R_q = 6.7 nm

Polishing Compatibility

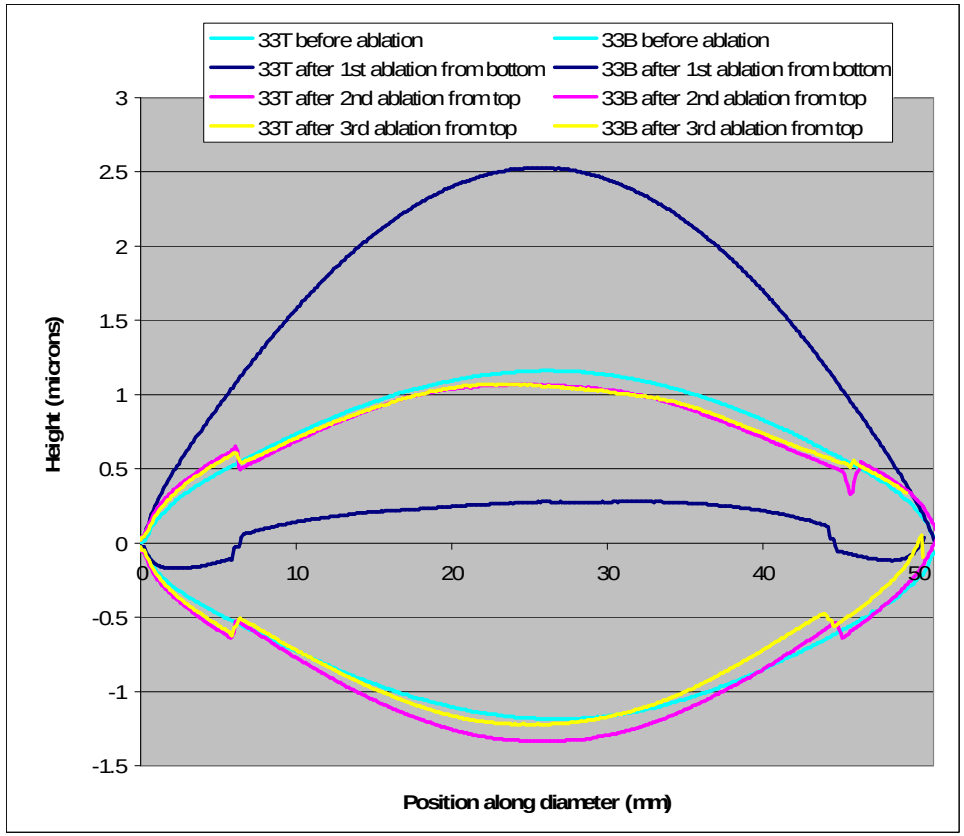
- Areas with laser induced Ra < 100 nm were readily polished back to the original Ra ~ 4 nm.
- Areas with Ra > 400 nm could be mitigated by polishing, but could not be returned to original smoothness, primarily due to pitting
- This puts a constraint on a laser machining process to maintain sufficiently low Ra



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
pre	10.6	51.6	545.7	543.2	614.0	594.3	980.3	734.5	936.6	1349.	2.5	4.7	16.5	3.8	7.4	19.8	5.7	12.2	80.2	6.6	10.0	16.1	3.5	7.3	20.3
post	3.9	14.0	164.6	152.2	142.5	212.7	671.8	225.6	458.3	1089.	3.7	3.8	5.5	3.3	3.5	4.9	4.7	4.4	6.4	3.8	4.0	4.1	3.9	3.5	4.4

Stress/Damage Mitigation

- Tests of picosecond ablation on Twyman stress of SiC ongoing in collaboration with Dr. Joseph Randi at EOC.
- Interferometry used to measure distortion of 50 mm diameter, thin, round disks after surface ablation.
- Figure shows example of how disk faces distort after ablation, consistent with removal of compressive stress left by polishing/grinding.
- Also using Raman to quantify distortion – still early in that work.



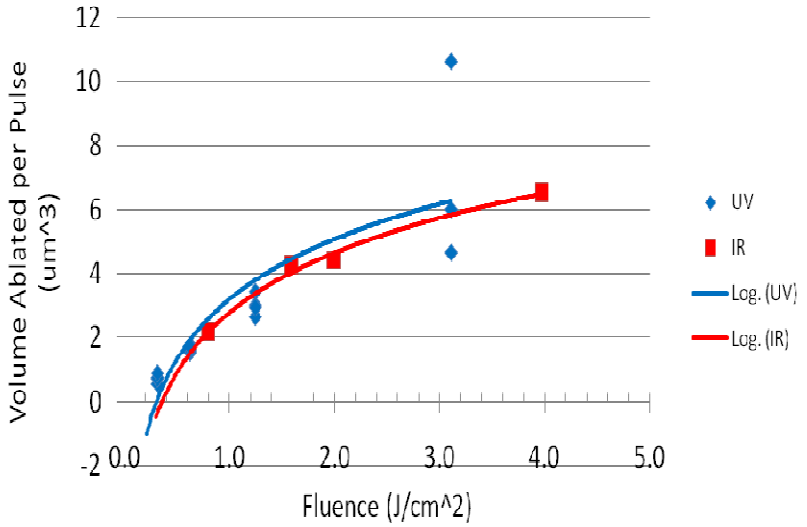
Twyman Distortion vs. Ablation

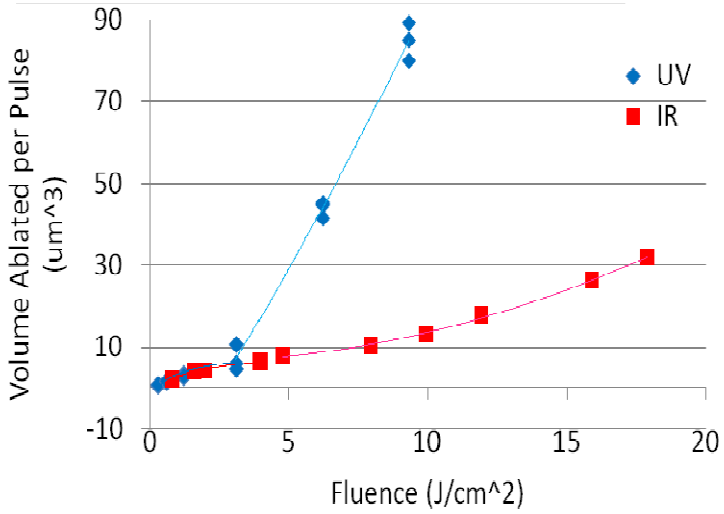
- Distortion with each ablation can be quantified by change in the optical power (~ 1/R) of each face.
- Comparable DP on first ablation, independent of ablation depth
  - Is depth of stress layer much thinner than previously thought?

		Ablation #				
Sample		1st	2nd	3rd	4th	5th
#2	Incr. Depth (nm)	6	0	15	15	
	ΔP (km^{-1})	11.7	-0.1	3.4	0.7	
#3	Incr. Depth (nm)	20	15	0	15	15
	ΔP (km^{-1})	10.5	-0.1	0.3	0.5	0.2
#6A	Incr. Depth (nm)	40	40	60	40	
	ΔP (km^{-1})	6.9	3.2	-2.8	1.4	
#6B	Incr. Depth (nm)	6	0	15		
	ΔP (km^{-1})	-5.2	-0.1	-5.7		
#34	Incr. Depth (nm)	400				
	ΔP (km^{-1})	10.5				

Ablation Rates

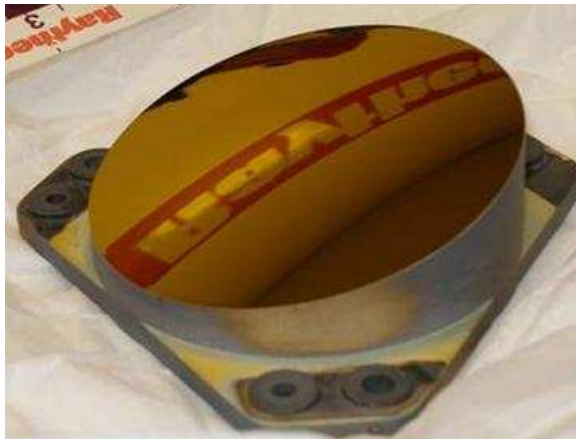
- Ablation at UV and IR wavelengths show similar behavior.
  - Threshold for ablation ~ 0.2 – 0.3 J/cm^2
  - Material removal per pulse grows logarithmically at low fluence, consistent with simple Bayes formula for optical penetration.
  - Above ~ 3 J/cm^2 the material removal increases quadratically, and machining quality is poor. In this regime, each ablation pulse is probably getting a thermal assist from its overlapping predecessors.





Upcoming Transition Tasks

- Machining demo components for SiC Afocal Telescope (SCATS)
  - Reduced size primary mirror
  - Full-scale tertiary mirror
- Application to mating surfaces.
  - E.g., pin and pad
  - Micron tolerances required.
- Integration of metrology into workstation
  - Benchtop white light interferometry
  - Confocal microscopy
- Some work on modeling picosecond pulsed laser ablation with Illinois Institute of Technology.



Conclusions

- Demonstration machining with direct focus workstation underway.
- Polishing compatibility study has defined limits of aggressiveness that can be used during laser ablation.
- Twyman testing continues to elicidate the degree to which grinding damage can be mitigated by ablation. This may be a process with spin-off value.
- Technology transition program to commence shortly and run for upcoming year.